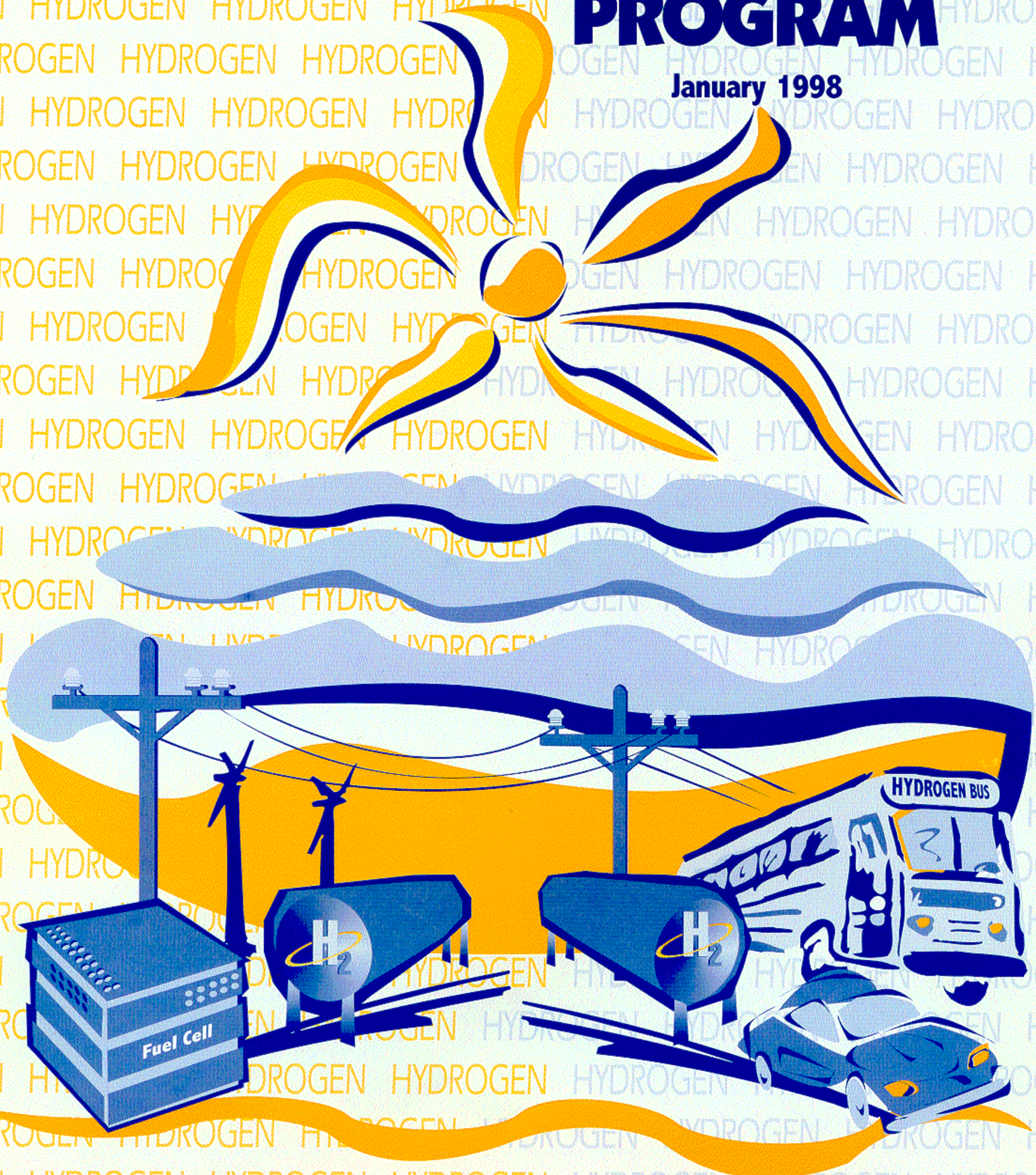
Strategic Plan for DOE HYDROGEN PROGRAM

January 1998



DOE HYDROGEN PROGRAM STRATEGIC PLAN

TWENTY-YEAR VISION

In the next twenty years, concerns about global climate change and energy security will create the platform for the penetration of hydrogen into several niche markets. Ultimately, hydrogen and electricity will come from sustainable renewable energy resources, but fossil fuels will be a significant transitional resource during this period. The growth of fuel cell technology will provide a base for the establishment of the hydrogen option into both transportation and electricity supply markets.

OVERVIEW

Strategies involving the Nation's energy supply are based on the need for energy and environmental security, and the ability to compete in the world market. Dependence on foreign energy resources is expensive. We suffer trade deficits and use our military to protect our energy supply abroad. Environmentally, the Nation is being forced to react both to the need for cleaner urban air and to the potential effects of global climate change. At the same time, while demand growth is projected to be slow at home, the growing worldwide demand for electricity will fuel international competitiveness. The solution is a clean, sustainable, domestic energy supply. Hydrogen can be one of the answers.

The opportunities for hydrogen are there. The changing electricity supply industry presents an opportunity for hydrogen as a fuel cell feedstock for distributed generation and cogeneration. As a storage medium, it can promote the use of renewable energy and lower the cost of peak electricity. In addition, the growing demand for electricity in the third world, some of it in locations that are not grid-connected, provides further opportunity for hydrogen as a storage medium.

The need for clean urban air presents the opportunity for hydrogen as a zero emission vehicle fuel stored on-board. At the same time, the use of hydrogen in this manner interfaces well with the desire for increasing the use of domestic resources for transportation fuels, thereby ensuring our national energy security.

Within the next decade, concern with potential global climate changes will become greater, forcing society to move toward energy resources that will minimize the emission of greenhouse gases. Hydrogen presents a potentially low-cost option for achieving the greenhouse gas minimization. It produces no carbon dioxide when it is used, and it can also be produced in ways that either do not produce CO_2 at all, or produce it in a manner and location that is amenable for CO_2 sequestration.

In 1990, Congress recognized the great potential for hydrogen as an energy carrier, and passed the Matsunaga Hydrogen Research and

PROGRAM MISSION

The U.S. Department of Energy Hydrogen Research and Development Program conducts research and engineering development in the areas of hydrogen production, storage, and utilization, for the purpose of making hydrogen a cost-effective energy carrier for utility, buildings, and transportation applications. This is being accomplished by:

Performing research projects that introduce renewable-based options to produce hydrogen and that decrease the cost of producing hydrogen from natural gas;

Developing hydrogen-based electricity storage and generation systems that will enhance the use of distributed, renewable-based utility systems;

Demonstrating fueling systems for hydrogen vehicles in urban non-attainment areas;

Developing and lowering the cost of technologies to produce hydrogen directly from sunlight and water; and

Supporting the introduction of safe and dependable hydrogen-based energy systems including the development of codes and standards for hydrogen technologies.

Development Act. This Act, a five-year plan, mandated the U.S. Department of Energy (DOE) to develop the critical technologies toward the implementation of hydrogen energy. The Matsunaga Act also mandated the establishment of the Hydrogen Technical Advisory Panel (HTAP), a body of hydrogen experts in industry and academia, who advise the Secretary of Energy on the status of and recommended direction for the furthering of hydrogen energy development. In 1996, Congress passed the Hydrogen Future Act, authorizing the spending of $164.5 million between 1996 and 2001 on the research, development, and demonstration of hydrogen production, storage, transport, and use. In support of this legislation, the DOE Hydrogen Program has been conducting the R&D and the technology validations which address the introduction of hydrogen into the energy mix in terms of both transition strategies and long-term results. The Program includes:

- Developing hydrogen production technologies for short-, mid-, and long-term targets.
- Developing low cost and low weight hydrogen storage technologies, addressing both stationary and transportation-based applications, as well as transport of hydrogen.
- Developing and optimizing methods for utilization of hydrogen in safe, efficient systems which produce little or no pollutants.
- Validating sustainable hydrogen systems for utility and vehicular applications.
- Evaluating and analyzing technologies and processes to identify the pathways that will enable hydrogen implementation.

The Hydrogen Program coordinates with a number of DOE programs that have hydrogen connections, including: the coal gasification and molten carbonate and phosphoric acid fuel cell programs under the Office of Fossil Energy, the direct conversion reaction program under the Office of Energy Research, the Proton Exchange Membrane (PEM) vehicle fuel cell program in the Office of Transportation Technologies, and the biomass gasification program within the Office of Utility Technologies. Currently, the Hydrogen Program is working with DOE's Offices of Transportation Technologies and Building Technologies on reforming, fuel cell, and energy storage activities.

In addition to electricity generation and road vehicle applications, hydrogen has potential as a fuel for airplanes, boats, and locomotives. Liquid hydrogen is the propulsion fuel currently used in the main rocket launcher for NASA’s space shuttle. European and Japanese efforts exist today for the development of hydrogen fueled aircraft. Research in the U.S. that lowers the cost of hydrogen production would also help these programs.

The DOE Hydrogen Program addresses long-term markets in both the utility and transportation sectors, markets in which high efficiency energy systems (i.e., fuel cells) will be fueled by environmentally benign, renewable hydrogen. The transitional strategy will use existing technologies to further hydrogen development while awaiting the maturation of the longer-term components. Interim development and demonstration will lead to near-term successes in niche markets, providing the needed visibility to industry and the public.

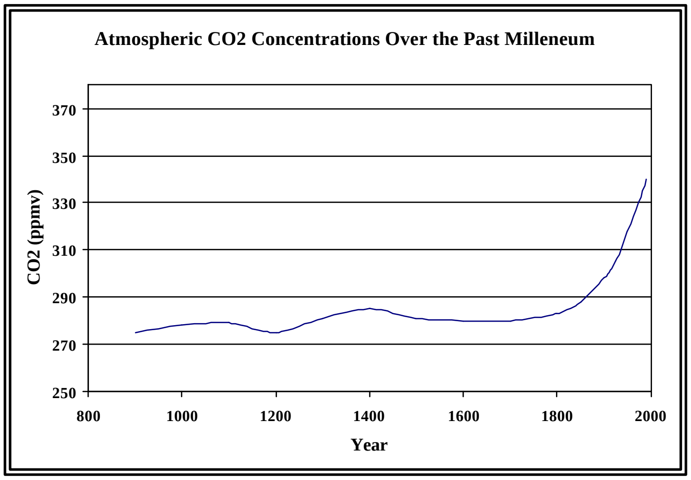
In this regard, refineries currently produce and use some 2500 billion scf of hydrogen per year. Much of the hydrogen is produced via natural gas reforming, and is used for preparation of heavy oil for cracking, for desulfurization, and for the manufacture of petrochemical products. An additional 1500 billion scf is produced by the chemical industry. The need for hydrogen in the refinery and chemical industries is growing at 5-10 percent annually. With this increased need, more hydrogen-producing plants will have to be built, or the capacity of current ones will need to be increased. This encourages industry to implement new and alternative technologies, including advanced natural gas reforming technologies, geared toward these goals.

These advanced natural gas reforming technologies when utilized, result in a lowering of emissions on their own. By enabling hydrogen utilization in the near-term, they also promote more advanced hydrogen technologies that incorporate renewable energy resources. These include biomass, hydropower, and wind technologies in the mid-term, and virtually inexhaustible supplies of water and sunlight in the long term.

SITUATION ANALYSIS

The Nation is striving for a secure, sustainable energy base that provides both local and global environmental benefits, and promotes competition in the international energy market. At the same time, the electricity supply sector is being restructured. The need for national energy security will promote the use of alternative fuels, while environmental concerns will promote renewable resources. Hydrogen can impact the electricity supply market as a distributed generation fuel and as a storage medium to convert baseload electricity into peak electricity, and can provide a clean fuel to power a vehicle. The existence of a large and growing non-energy hydrogen market provides the arena for near-term hydrogen technology gains. The existence of long-term focused research on using renewable energy sources to produce hydrogen from water provides the means to develop a completely renewable, non-polluting energy source.

CONCERN IS INCREASING OVER GLOBAL CLIMATE CHANGE BEING CAUSED BY INCREASING EMISSIONS OF GREENHOUSE GASES SUCH AS CO_2. ONE-THIRD OF THE AMOUNT OF CARBON-BASED EMISSIONS IN THE U.S. IS DUE TO THE GENERATION OF ELECTRICITY; ANOTHER THIRD IS EMITTED AS A RESULT OF THE TRANSPORTATION SECTOR. AN INCREASE IN THE USE OF RENEWABLE ENERGY AND CO_2 SEQUESTRATION TECHNOLOGIES WILL HELP TO REDUCE THESE EMISSIONS. HYDROGEN PROVIDES APPROACHES FOR BOTH OF THESE OPTIONS.



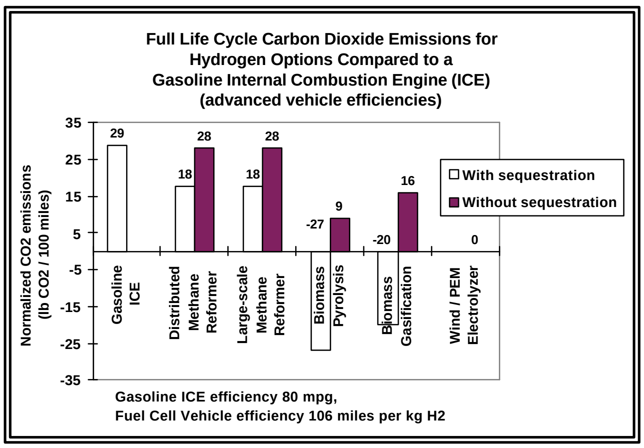
CO_2 concentrations in the atmosphere are increasing rapidly, giving rise to more concern about global climate change. Studies of air bubbles in dated ice-core samples have indicated an essentially constant amount of CO_2 in the atmosphere for the greater part of the Second Millenium – about 280 ppm. With the onset of the Industrial Age during the Nineteenth Century, however, a rapid rise was initiated. This rise has continued at an increasing rate up to the present time. The atmospheric CO_2 concentration is now over 370 ppm, with the rate of increase projected to continue to grow, especially in light of both worldwide population growth and the industrial growth in such populous countries as China and India. Projections indicate a doubling of CO_2 concentrations from pre-industrial values by 2030, and a trebling by 2100. Models predicting the effect of unabated increases in CO_2 concentration on our climate have warned of the potential of a several degrees increase in our temperature by 2100, especially in the colder regions.

The recognition of the need for global climate change mitigation is becoming more prevalent; and at the Rio Earth Summit in 1992, the United Nations Framework on Climate Convention was adopted. Its ultimate objective is to stabilize greenhouse gas emissions, including CO_2, at a level that will not affect climate. The Convention's ultimate authority, the Conference of Parties (COP), meets periodically, with the third meeting scheduled for Kyoto in December 1997. The COP is expected to adopt a protocol or another legal means to commit developed countries to reduce their greenhouse gas emissions after 2000.

In the U.S., about one third of the CO_2 emissions comes from the transportation sector, while another third comes from the processes necessary to generate electricity for the other three sectors (residential, commercial, industrial). Two paths that lead to an overall reduction in CO_2 emissions involve increasing the amount of renewable resources in the mix, and sequestering a portion of the CO_2 produced from fossil fuels. Hydrogen can play a significant role in both scenarios.

Reforming of natural gas to hydrogen provides a platform for CO_2 sequestration. The reforming process produces as a byproduct a relatively pure form of CO_2 that lends itself to capture much more conveniently than does combustion of natural gas itself. Hydrogen can be produced from natural gas and stored on-board a fuel cell powered vehicle, or it can be blended with natural gas for reduced CO_2 emissions.

On a CO_2 emissions basis, natural gas is a superior feedstock compared to gasoline, as it has a lower carbon-to-hydrogen ratio. However, as emission reduction and efficiency technologies for gasoline become more advanced, as shown in the accompanying figure, the advantage is much reduced. Reforming the natural gas to hydrogen and sequestering byproduct CO_2 results in nearly 40 percent less life-cycle CO_2 emissions than the advanced gasoline scenario. With a biomass feedstock plus sequestration, life-cycle CO_2 emissions are actually negative.



In the electricity generation area, electrolysis is seen as a renewables-enabling technology. The most logical scenario for the nearer term is to transmit renewable resource-produced off-peak electricity to the load site. Electrolysis and hydrogen storage occurs at the site, with subsequent regeneration of peak electricity. Eventually, a hydrogen transport infrastructure will be developed. There will then be an option for an electrolyzer to be sited at the renewable source and hydrogen to be transported by pipeline. The pipeline infrastructure also lends itself to a CO_2 sequestration scenario.

CO_2 sequestration technology presents a clean bridging strategy for the eventual implementation of hydrogen from renewable resources. The need for global climate change mitigation will also promote the development of PEM fuel cells, thereby helping to create a position for hydrogen. Hydrogen produced from renewable resources (such as wind power, hydropower, or sunlight and water) is a non-polluting energy form produced from virtually inexhaustible sources. There are several biological and electrochemical photolytic-based technologies that convert water to hydrogen. Technical progress is needed to bring photolysis efficiencies up and hydrogen production costs down at least to the $12-15/MMBtu level.

RESTRUCTURING WITHIN THE ELECTRIC POWER INDUSTRY IN THE U.S., AND WORLDWIDE ELECTRICITY DEMAND, CAN HELP TO DEFINE A ROLE FOR HYDROGEN AS A FUEL FOR DISTRIBUTED GENERATION AND AS AN ELECTRICITY STORAGE MEDIUM FOR RENEWABLE ENERGY.

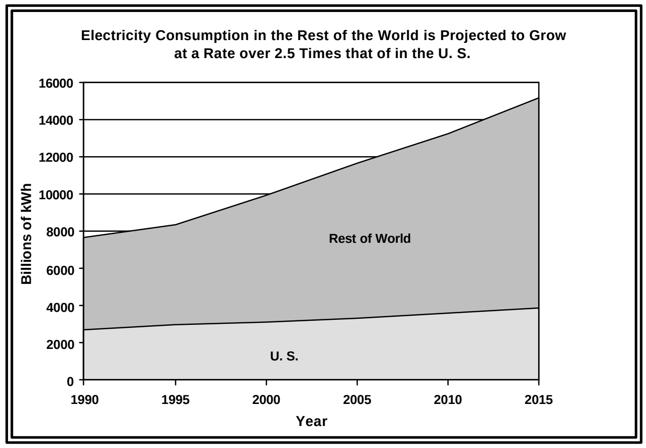
As the U.S. electric power industry becomes restructured, it opens the door for more competition and customer choice. This will likely lead to more distributed generation, and will also provide more of a platform for the implementation of renewable energy. It will thus provide one means of addressing the aforementioned global climate change mitigation, and serve as an enabling tool for hydrogen.

According to the 1997 edition of the Energy Information Administration's *Annual Energy Outlook*, the 1995 capacity for electricity generation in the U.S. from renewable resources (including hydro) was about 94 gigawatts. Renewable electricity generation is projected to rise to 104-110 gigawatts by 2015. Global climate change mandates and consumers choosing green power are two potential factors that could lead to an even larger amount of renewables. Hydrogen can serve as a storage medium for low-cost renewable-sourced baseload power such as geothermal and hydroelectric, increasing its availability for peak power. Wind is another potential renewable energy source that can benefit by coupling with hydrogen storage. Wind is an intermittent resource, with a capacity factor about 35%. An efficient use of wind power can be reached if the surplus wind power generated during off-peak electricity usage hours generated hydrogen. Progress in wind turbine technology has led to projections that the cost of electricity from good wind sites will be about 2.5 to 3.5 cents per kWh by 2000. Using hydrogen to store this relatively inexpensive, renewable-based off peak power and then reconverting it to electricity during peak periods can result in less expensive peak power. Hydroelectric power is already very inexpensive, often less than 1.5 cents per kWh, and provides another resource for this concept.

The use of an on-site hydrogen storage system presents an attractive scenario. Although storage alternatives exist, the hydrogen option enables the use of reversible fuel cells, permits the potential of cogeneration of heat and electricity, and provides the opportunity to produce excess hydrogen, with the excess being available for transportation systems or for the merchant hydrogen market. This integrated system which depends on hydrogen storage is a low-cost alternative to similar systems that may use different storage technologies. Restructuring within the U.S. electricity supply sector is likely to favor smaller and “non-traditional” distributed systems, and in fact, will help to create new power producers that can compete with existing utilities. The type of integrated system described here fits in well with this scenario.

The ongoing transition to distributed generation provides a role for hydrogen in the electricity supply market. There are currently about 30 phosphoric acid fuel cells in operation in the U.S., all are manufactured by International Fuel Cells (IFC), each having 200 kW capacity. An integrated reformer converts natural gas to a hydrogen rich fuel for the electrochemical cell. This system works best in a cogeneration scenario where excess heat needed to operate the reformer can satisfy a heat load as the cell provides electricity.

The U.S. electric power industry overall is currently experiencing a slow but steady growth in the demand for electricity, currently about 1.3% per year. Worldwide demand growth, on the other hand, is much more rapid, and is projected to approach 4% per year through 2015. This will include large increases in demand in third-world countries including some areas where connection to an electricity grid is impossible or impractical. Since there is no infrastructure in place, an opportunity exists for the implementation of stand-alone and cogeneration systems involving renewable-based hydrogen technologies. Big U.S. companies are becoming increasingly interested in the world electricity market; a DOE role of aiding in the development of hydrogen technologies will help steer these companies toward including a role for hydrogen.



THE PRESENCE OF URBAN NON-ATTAINMENT AREAS PROVIDES A RATIONALE FOR THE DEVELOPMENT OF LOW- OR ZERO-EMISSION VEHICLE FUEL. NATIONAL SECURITY CONCERNS PROVIDES ADDITIONAL IMPETUS BY ENABLING AN ALTERNATIVE VEHICLE MARKET.

Many cities in the U.S. have been classified as air quality non-attainment areas (as defined in the 1990 amendments to the Clean Air Act) by the Environmental Protection Agency, largely due to vehicle emissions. This has resulted in the need for the development of alternatively fueled vehicles that produce lower or no emissions. This is best shown by the existence of the mandate in California that 10% of all new vehicles offered for sale be "zero emission vehicles" (ZEV) by 2003.

Electric vehicles using on-board batteries (BEV) are being developed to meet ZEV requirements. While significant progress has been made in this area, BEVs provide limited driving range (80-150 miles), and the batteries also represent a toxicity problem upon their disposal.

At the same time, our concern with national energy security is leading us to explore alternative vehicles – those that rely on a domestic fuel. Natural gas is one obvious option from both security and environmental standpoints. Hydrogen, if the cost delta from natural gas is low, will also be promoted by this scenario.

Some automobile companies and the natural gas industry are promoting the use of natural gas to fuel internal combustion engines which will, with proper power system modification and post combustion catalytic clean-up, produce reduced emissions. Facilities owned by the U.S. Department of Defense, as well as many state governments, utilities, and private companies use natural gas to fuel their fleet vehicles. These could be converted to hydrogen, or hydrogen could be blended into the natural gas, again with the proper modifications, to further reduce emissions. Using hydrogen would result in lean combustion, which greatly reduces NO_x emissions. No emission-controlling catalysts are then needed.

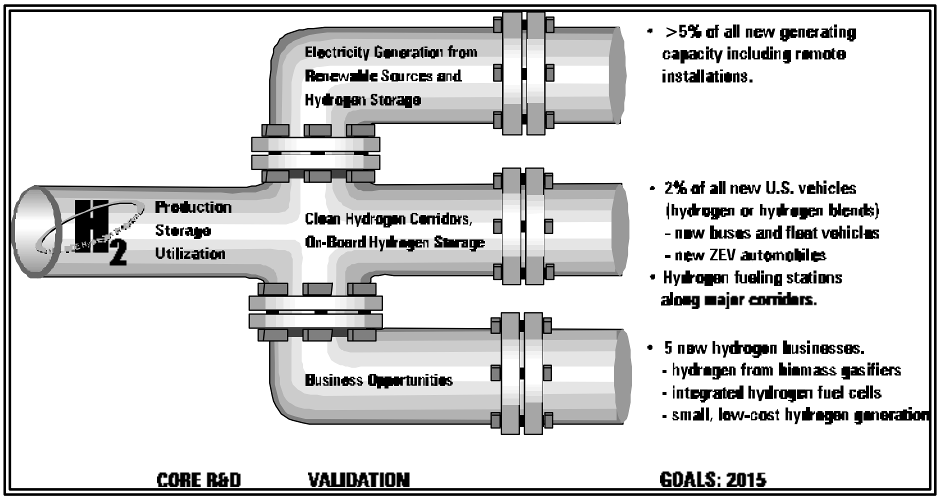
A fuel-cell-powered vehicle is about 2.5 times as efficient as a conventional internal combustion engine (ICE) burning gasoline, and about 25% more efficient than a hybrid system that includes an ICE burning hydrogen. For vehicular applications, PEM fuel cells hold the most promise because they operate at a much lower temperature (90^{o}C) than do other types of fuel cells, thereby enabling more rapid start-up.

The "Big 3" automobile companies, as part of the DOE/industry Partnership for a New Generation of Vehicles (PNGV) program, are investigating fuel cell vehicle systems that use either carbon-based liquid fuels or hydrogen stored on-board. The liquid fuels are reformed on-board to a hydrogen-rich gas to feed the PEM fuel cell. This can provide the framework for the development of gaseous (hydrogen) on-board fuel cell systems. The vehicle system can be converted to a gaseous system by using a hydrogen storage system in place of a liquid storage system and reformer.

The constant-dollar price of natural gas in 2015 is projected to be about $2.50 per million Btu, the same as today, thus making it an excellent hydrogen production feedstock for the next twenty years. In addition, the production and use of hydrogen first from natural gas and then from renewable resources allows the U. S. to increase its self-sufficiency in transportation fuels, providing for increased energy security.

HYDROGEN PIPELINE TO THE FUTURE

In order to enable a future that includes hydrogen energy, the DOE Hydrogen Program should pursue a program management structure that continues a strong core R&D effort that produces products that can be validated via an industry-led program. The technology validation efforts, including 50/50 cost-share arrangements, serve as a conduit to the marketplace



Core R&D: Products to the Pipeline

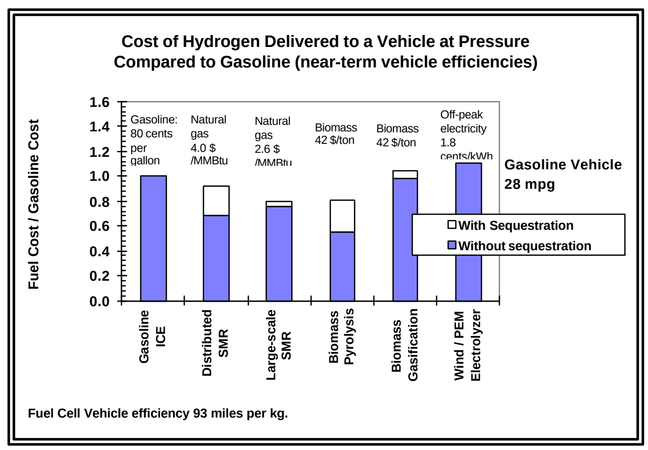
The DOE Program will continue to support a transitional strategy with efforts that lead to cost-effective and emission-free production of hydrogen from natural gas. A target cost of hydrogen produced via these technologies is \$6 to \$8/MMBtu. Areas for potentially lowering the incremental cost include methods to lower the temperature of steam reforming, increase the net rate of hydrogen production, or improve the hydrogen purification system.

Hydrogen can also be produced by the gasification or pyrolysis of dedicated biomass crops for approximately \$6 to \$8/MMBtu. Both the natural gas and biomass strategies can be augmented by including CO_2 sequestering. Even including sequestration costs, hydrogen can be produced by these technologies and delivered to a vehicle less expensively than gasoline on a miles per gallon equivalent basis when compared with today's 28 miles per gallon efficiencies.

In order to achieve its ultimate goal, hydrogen from sunlight and water, the Hydrogen Program will pursue long-term photoelectrochemical and photobiological research and development, with a target cost for hydrogen of \$10-\$15/MMBtu.

The direct utilization of hydrogen on-board a vehicle requires a storage system that is lightweight and low-volume, has a high energy density, is reusable or rechargeable, and is safe.

Current hydrogen storage methods include high-pressure storage of gaseous hydrogen and low-temperature storage of liquid hydrogen. Hydrogen can also be stored physically and/or chemically in carbon structures, metal hydrides and organometallic polyhydrides.



A reversible electrolyzer/fuel cell system enables the increased utilization of renewable technologies such as wind and hydroelectric power. A single unit that acts reversibly as both an electrolyzer and a fuel cell will result in a significant reduction in capital equipment cost and somewhat reduce the land requirement for such a system. There have been projections by industry that they believe that the cost of reversible PEM fuel cells will be about \$600-\$1000/kW by 2002.

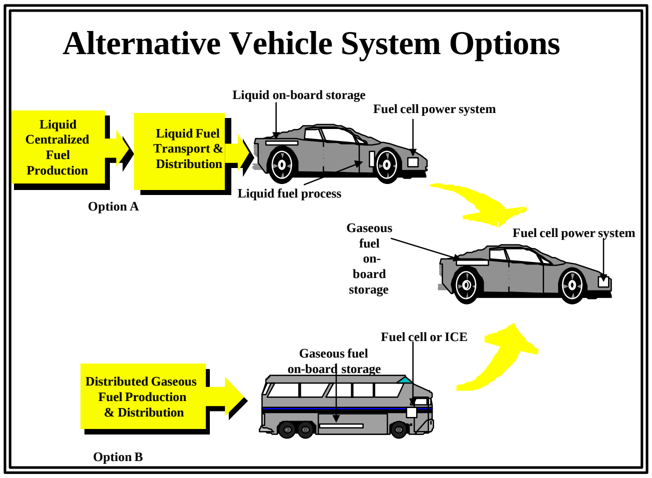
For hydrogen to be accepted by the public, it must be considered safe. Steps toward this end can be accomplished by modeling hydrogen leak behavior and by developing rapid, sensitive hydrogen leak detection systems.

Technology Validation: Conduits to the Market Place

The Hydrogen Program's technology validation section serves as a means by which the developing systems are deployed in an operating environment. The Program's strategy involves exploring with industry three areas of validation:
1) renewable/hydrogen utility systems,
2) hydrogen clean clusters and corridors, and
3) opportunities for other early business opportunities identified by industry. The technology validation effort is industry led and designed to develop industry commitment. Cost-sharing provides industry an opportunity to reduce the technical and financial risks associated with validating hydrogen systems. The private sector can later bring these systems to the market place independently. Also, Program funding can be leveraged by coordination of efforts with other groups. This includes DOE's Offices of Fossil Energy and Building Technologies in the electricity supply area. In the transportation sector, coordination of efforts include the U.S. Department of Defense's Alternative Fuel and Defense Conversion Programs, and DOE's Office of Transportation Technologies.

The renewable/hydrogen utility systems strategy is aimed at integrating hydrogen production, storage, and end-use systems with electricity generated from existing or planned renewable resources. This is meant to provide assistance to industry for mid-term (5-10 years) hydrogen system applications, which will then lead to the longer-term installation of privately funded larger integrated systems. This draws on R&D technologies involving reversible, PEM stationary fuel cells, as well as hydrogen coproduction with electricity. One option is an exploration of reversible halogen-based fuel cells. These operate at a lower voltage than do water-based systems, thus providing a higher round-trip efficiency.

The hydrogen clean corridor strategy addresses both the development of a hydrogen infrastructure for transporting hydrogen to a particular end use and that particular end use. It will initially stress vehicles with dedicated functions such as buses or fleet vehicles. The Program will identify these dedicated clusters, which can eventually be linked together to form a clean corridor. The cluster strategy will be geared toward vehicles that have hydrogen on-board much like Option B in the Figure below. It will lead to the development of hydrogen fueling stations using both natural gas and renewable resources to provide hydrogen for vehicles. This will enable the transition from a hydrocarbon liquid to a gaseous fuel system for the transportation sector. The project includes demonstrations of integrated engine /fuel storage/delivery subsystems and utilization of hydride bed subsystems in fuel cell vehicles.



The third validation strategy involves the periodic release of solicitations. Responses by industry to DOE solicitations provide the Program with information regarding industry interest and buy-in for hydrogen systems. These solicitations give U.S. companies the ability to compete in niche markets as well as giving them a cost-shared inroad to the international marketplace. The responses also identify the technologies that are candidates for accelerated development. The cost-shared awards are intended to promote the desire of industry to enter the market place. These awards are in the areas of biomass gasifiers for hydrogen production, near-term integrated hydrogen fuel cell systems, and small, low-cost hydrogen generation systems.

GOALS OF THE HYDROGEN PROGRAM

The use of hydrogen as a fuel and energy carrier can provide options toward achieving our national strategic goals of energy security, environmental security, and international competitiveness. To enable this, the goals of the Hydrogen Program itself must be identified and reached. These goals must set the course for the Technology Development and Technology Validation portions of the Program, and must also address environmental and policy issues. In addition, strategic goals are needed that will provide the structure for incorporating analysis and outreach activities to support and further the development and validation activities that will lead hydrogen technologies to the market place.

Technology Development Goals

Improve the efficiency and lower the cost of fossil-based and biomass-based hydrogen production processes to $6-$8/MM Btu.

Advance emission-free, and renewable-based hydrogen production technologies towards commercial viability, with a target cost of $10-$15/MMBtu.

Demonstrate safe and cost-effective storage systems for use in stationary distributed electricity generation applications, and for on-board and stationary applications in urban non-attainment areas.

Develop fuel cell and reversible fuel cell technologies as an efficient low-cost means of converting hydrogen into electric power.

Strategic Issues

Initially, hydrogen utilized in fuel cells will be produced from natural gas. The competing option will be to burn the natural gas or natural gas/hydrogen blends in combustion turbines or internal combustion engines. To make fuel cells competitive with respect to the combustion options, the cost differential between hydrogen and natural gas must be minimized.

Because it lacks an infrastructure, hydrogen transport is expensive. Although transport of liquid hydrogen is an option, there is an advantage in co-locating hydrogen production with end-use early in the program. Small-scale hydrogen production systems are needed to serve hydrogen-fueled vehicles and distributed electricity generation systems.

Ultimately, renewable-based, emission-free hydrogen production technologies using resources such as water and sunlight or wind must be developed and made cost-effective if hydrogen energy systems are to provide an increased environmental benefit.

The market barriers facing alternative hydrogen production technologies include: the low cost of natural gas, the low cost of the large-scale steam reforming process, and the fact that carbon dioxide emissions are not presently regulated or taxed.

Major improvement in hydrogen storage performance will be necessary for hydrogen to gain in acceptance as an effective energy carrier. Strategic issues for hydrogen storage include the need for safe, lightweight, low-volume, and low-cost on-board storage. Safety and low-cost are important issues for stationary storage as well. Storage R&D projects emphasize improved performance and exploration of new options.

The major concern for high-pressure storage of hydrogen fuel is safety. Modeling and experimental studies are needed to develop light weight materials and fabrication techniques which exhibit benign failure modes, excellent fatigue properties, and are not affected by environmental and hydrogen exposure.

Hydrides are inherently safer for storage, but require improvements in weight density and cost. Low cost manufacturing processes and lightweight, low-cost alloys with high hydrogen capacity are needed.

Carbon-based materials such as nanotubes, fullerenes, and graphitic fibers all show promise as high-density storage media. Research shows that these materials store hydrogen at near room temperature or above, eliminating the cryogenic requirements of earlier materials. These systems are in early stages of development and will require additional research before their storage capabilities can be fully assessed. Issues include matrix manufacture, durability, and quantity of hydrogen stored.

In order to eventually develop a hydrogen infrastructure, the end-use technologies must be developed and matured. Here, the primary technology is the fuel cell. In order for fuel cells to be the "work horse" hydrogen utilization tool, several technical hurdles must be traversed. Fuel cells must be run on hydrogen directly to prevent CO_2 emissions; fuel cell efficiencies must be increased and their cost must be lowered to make them competitive; and reversible electrolyzer/fuel cell modules must be developed that can enable substantial reductions in overall system costs.

Strategic Objectives

- Demonstration of advanced natural gas-based hydrogen production technologies with higher efficiencies and lower capital cost than conventional steam methane reforming.
- Demonstration of small-scale hydrogen production processes serving transportation and utility sector applications.
- Development of biomass/MSW -based hydrogen production processes.
- Continued research and development of photoelectrochemical and photobiological hydrogen production processes, focusing on improved solar efficiency.
- Facilitate the use of hydrogen as a vehicular fuel through (a) modeling and experimental studies to verify the safety of high-pressure gas storage and (b) developing advanced storage technologies for on-board applications.
- Develop lower cost storage technologies and demonstrate their competitiveness in integrated renewable energy systems.
- Develop a low-cost reversible fuel cell.
- Enable the development of more reliable, less expensive sensors.

Technology Validation Goals

Support industry in the development and demonstration of hydrogen systems in the utility and transportation sectors.

Strategic Issues:

In order for hydrogen to be a viable long-term option, it is necessary for some shorter-term strategies to be implemented. Validating hydrogen concepts and projects in the utility and transportation sectors will show that hydrogen has near-term potential, and will thus lead toward achieving the longer-term goals. Since the Hydrogen Program is targeting both the utility and transportation markets, it is essential that niches be found in both areas that will allow near-term demonstration of the hydrogen technologies. On the utility side, a key program need is the demonstration of technologies that will enable the integration of renewable resources. This can be provided, for example, by the integration of a wind turbine, electrolyzer, hydrogen storage device, and gen set to provide less expensive peak power to a remote location. In the transportation sector, clean hydrogen clusters can be developed. These will consist of a limited infrastructure that will provide hydrogen for a particular end-use, and the end-use itself. A near-term example might be the use of small-scale steam reforming, partial oxidation, or plasma reforming to convert natural gas to hydrogen at the site of a refueling station. The hydrogen is then transferred to an on-board storage system on a fleet of vehicles, and powers these vehicles through either fuel cells or hybrid ICEs. Over a period of time, these clusters will combine into a clean corridor, providing a means of hydrogen-based travel between two cities.

During the course of the Program, other potential markets for hydrogen-based energy may become more attractive. These could include hydrogen-fueled aircraft, boats or trains. The Program must continue to monitor these potential markets and provide support when appropriate.

The ultimate measure of hydrogen safety will be the development of new consensus standards, certification tests, and demonstrated operating experience acceptable to safety officials and regulations. Hydrogen validation projects must address these issues.

As mentioned above, the Hydrogen Program employs as a strategy, the periodic release of solicitations to industry in order to obtain industry's buy-in to the various hydrogen technologies. It is necessary to require industry to provide substantial business plans as well as cost-sharing in order to participate. Industry's promoting public awareness is another requirement.

Strategic Objectives:

- Obtain industry participation through competitive solicitations.
- Integrate renewable energy resources with hydrogen storage in remote distributed power scenarios.
- Demonstrate hydrogen production, storage, and refueling stations within several clean clusters with evolution into clean corridors.
- Demonstrate hydrogen-based operating experience acceptable to safety officials.

Environmental Goals

Reduce emissions in urban non-attainment areas.

Reduce global greenhouse gas emissions.

Strategic Issues:

Hydrogen energy technologies offer unparalleled potential for improvements in environmental quality. These improvements are not guaranteed, however, for although hydrogen itself is clean, it must be produced from other materials that may produce environmentally harmful byproducts. In electricity generation, simply moving from coal to natural gas reduces emissions. Using hydrogen produced from fossil fuels or biomass at a remote site can move emissions away from the non-attainment area. By using renewable resources to produce hydrogen, the electricity is virtually emission-free.

A transition to hydrogen-fueled automobiles and other vehicles can virtually eliminate urban air pollution and reduce carbon dioxide emissions. This will occur either through using renewable energy sources, by producing hydrogen from natural gas using a means that does not produce CO_2 such as pyrolysis, or by sequestering carbon dioxide from fossil fuels used at central hydrogen production facilities. Initially, even the use of natural gas reduces the amount of pollution compared to the use of gasoline.

As a result of the Clean Air Act amendments in 1990, California has become the first jurisdiction to mandate that 10 percent of new vehicles sold be ZEVs by 2003. Other urban non-attainment areas may follow with their own ZEV or near-ZEV policies. If hydrogen is to make an impact in non-attainment areas, the technologies leading to its utilization in these areas must be in place.

Strategic Objectives:

- Analyze and compare the full environmental benefits achievable using hydrogen energy. This should include thermochemical and electrolytic hydrogen production, and use of hydrogen both in the utility and transportation sectors.

Policy, Planning, and Analysis Goals

Ensure that Federal R&D investments in hydrogen production, storage, distribution, and end-use technologies will provide the maximum value added to national strategic goals including global greenhouse emission mitigation.

Identify and evaluate key market segments and market entry conditions for hydrogen utilization in transportation and in electricity generation at distributed and remote locations.

Develop and apply metrics to measure the Program's contribution to attaining national strategic energy goals and market share in key market segments.

Strategic Issues:

The goals of supplying significant amounts of renewable hydrogen to the electricity supply and transportation markets in 20-30 years cannot be achieved with current budgets unless they are highly leveraged with other Federal programs and with industry. The key planning and analysis issue for the Program is how to define and maximize its "value-added" to the national and global transition to renewable hydrogen energy. Such transition is essential to sustain economic development, provide national energy security, be internationally competitive, and mitigate global climate change.

In order for policy makers to make rational decisions regarding the utilization of hydrogen, it is necessary that they receive the pertinent information and recommendations from the Program and industry. These recommendations must evolve from data developed from the development and validation components of the Program, and must incorporate reasonable and thorough systems analysis of hydrogen integrated pathways.

Strategic Objectives:

- Prepare a portfolio analysis that (1) defines specific market criteria to guide R&D investment priorities for hydrogen as a competitive fuel in stationary and mobile applications in air quality non-attainment areas, and (2) defines strategic criteria to guide R&D investments to enhance global competitive leadership in hydrogen technology development. The portfolio analysis will help define an R&D investment strategy and portfolio management plan to allocate R&D resources over the next 5 years.

- Characterize key market segments, by market size, end-use patterns, time-dependent cost/performance and other critical market entry criteria, consumer requirements and preferences, private sector investments and production requirements, government investments and incentives/regulations, competing fuels and technologies, and potential return on private and public investments. Define pathways and transition strategies to attain a given share of these markets for hydrogen-fueled technologies. Identify and assess key technology development baselines for market entry and penetration.

- Perform technical and economic analyses on hydrogen integrated pathways in order to ascertain the proper routes to hydrogen implementation.

- Develop a programmatic database that includes metrics to measure the Program's contribution to the attainment of national strategic objectives and market share in key market segments. The database will incorporate data on cost, performance, reliability, lifetime, and other key characteristics for hydrogen technologies to contribute to national strategic energy objectives and compete in key market segments.

Outreach and Coordination Goals

Develop informed constituencies in the industrial and public sectors as part of a strategy to accelerate the commercialization of renewable hydrogen technologies.

Strategic Issues:

The use of hydrogen as a clean, safe, and reliable fuel and energy carrier, is a potentially important means of enabling our national strategic goals of energy security, environmental security, and international competitiveness. This scenario is becoming a stronger possibility with the increased emergence of fuel cells bringing hydrogen closer to the market place. In addition, the significant strides toward hydrogen commercialization by such companies as Ballard (Canada) and Daimler-Benz (Germany) are creating a strong international presence. It is therefore important to include in the Hydrogen Program effort, an effective outreach and coordination component to keep people informed, and to effectively participate in and compete with the international effort.

Industry has compiled an impressive safety record producing and using large quantities of hydrogen year after year. The safe handling of hydrogen through adherence to established industry practices and procedures needs to be communicated to industry and the public at large.

Continued and sustained progress in hydrogen R&D is linked to continued improvement of our educational infrastructure. By supporting world-class R&D in advanced hydrogen production, storage, and utilization, the Hydrogen Program plays a role in improving the educational infrastructure the U.S. needs in order to compete in the coming century. This link between the Hydrogen Program and the nation's critical educational infrastructure must be exploited.

Finally, there is a need for clear comprehension and coordination of all hydrogen energy-related work being undertaken by other DOE offices and Government agencies, as well as an enhanced interface with state, local, and foreign governments. Also, a strong tie is needed with private industry, including hydrogen representation by the National Hydrogen Association (NHA). The role of the NHA includes interests that lead to the commercialization of hydrogen. Thus, a strong Hydrogen Program/NHA bond is essential.

Strategic Objectives:

- Develop a 5-year Outreach Plan that integrates public, industry, and educational outreach activities that together will improve understanding of the pivotal role hydrogen will play in creating a sustainable energy, economic, and environmental future.

- Identify the key constituencies that must be better informed about hydrogen and prepare the materials and tools needed to inform these constituencies.

- Coordinate Program efforts with other DOE offices and other government agencies. Be cognizant of efforts of state and local governments as well as foreign interests. Work with private industry and the NHA.

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